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TURBULENT ADVANCES OF BREAKING BORES: EXPERIMENTAL OBSERVATIONS

AUTHORS: Xinquian LENG and Hubert CHANSON

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Turbulent Advances of Breaking Bores: Experimental Observations

by

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Breaking tidal bore of the Qiantang River in the northern channel downstream of Xinchang, China on 6 September 2013 at 11:50

ABSTRACT

In an estuary, a tidal bore is a positive surge generated at the leading edge of the flood tidal wave during the early flood tide under spring tide conditions in a narrow funnelled channel. After its formation, the bore front may be analysed as a hydraulic jump in translation. For Froude numbers greater than 1.4 to 1.6, the leading edge of the bore is characterised by a breaking roller. The roller is associated with a sudden increase in water depth, a highly turbulent flow with large-scale vortical structures, some kinetic energy dissipation, a two-phase air-water flow region and strong turbulence interactions with the free surface associated with splashes and droplet ejection. New unsteady experiments were conducted in a 19 m long 0.7 m wide canal to investigate the upstream propagation of breaking bore roller. The roller toe propagation was a highly turbulent process. The toe perimeter shape fluctuated rapidly with transverse distance and time, and its transverse fluctuations were quantified in terms of the standard deviation $(X-X_{median})'/d_1 = 0.145$ at a given time. The characteristic transverse wave length of the toe perimeter was approximately 1.2 times the initial flow depth d_1. Both the standard deviation of toe perimeter location and characteristic transverse wave length were comparable to field observations in the Qiantang River bore (China). The celerity of the roller toe fluctuated rapidly with time and space, although in a quasi-two-dimensional manner on average. The sidewalls had little effect on the upstream propagation of the roller within the experimental flow conditions. The instantaneous longitudinal free-surface profile of the roller showed significant temporal and spatial fluctuations. The standard deviation of the free-surface elevation was maximum in the first half of the roller and the data were comparable to previous studies in breaking tidal bores and stationary hydraulic jumps for comparable Froude numbers. For $Fr_1 < 2$, a gradual rise in free-surface was clearly seen in front of the roller, and both the roller toe elevation and its vertical fluctuations decreased with increasing Froude number. New air-water flow measurements highlighted some distinctive air bubble entrainment at the toe of the roller. Bubbles with larger chord times were detected at higher vertical elevations in a more intermittent manner. Overall the study demonstrated that the propagation of breaking bore was a very turbulent process. Although the bore may be analysed as a hydraulic jump in translation in an integral form, in first approximation, the rapid fluctuations in roller toe perimeter and free-surface profiles indicated a strongly, three-dimensional flow motion.

Keywords: Breaking bores, Tidal bore, Roller shape, Roller toe perimeter, Longitudinal roller profile, Roller toe elevation, Bore celerity, Air bubble entrainment, Jump toe, Turbulence, Physical modelling.

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LIST OF SYMBOLS

The following symbols are used in this report:

A	channel cross-section area (m^2);
A_1	initial channel cross-section area (m^2) immediately prior to the tidal bore passage;
A_2	conjugate cross-section area (m^2) immediately after the bore passage;
B	free-surface width (m);
B_1	initial free-surface width (m) immediately prior to the tidal bore passage;
B_2	conjugate free-surface width (m) immediately after the bore passage;
c	instantaneous void fraction: c= 0 in water and c= 1 in air;
d	water depth (m);
d_1	initial water depth (m) immediately prior to the tidal bore passage;
Fr	Froude number;
Fr_1	tidal bore Froude number defined as: $Fr_1 = \frac{V_1 + \overline{U}}{\sqrt{g \times \frac{A_1}{B_1}}}$ for a stationary hydraulic jump in a rectangular channel: $Fr_1 = \frac{V_1}{\sqrt{g \times d_1}}$
f	Darcy-Weisbach friction factor;
g	gravity acceleration (m/s^2): $g = 9.80\ m/s^2$ in Brisbane, Australia;
k_s	equivalent sand roughness height (m) as defined by NIKURADSE (1932);
L_r	roller length (m);
L_w	transverse wave length (m) of roller toe perimeter;
Q	water discharge (m^3/s);
S_o	bed slope: $S_o = \sin\theta$;
t	time (s);
t_{toe}	time (s) of passage of roller toe;
U	celerity (m/s) of the bore roller toe positive upstream;
U'	standard deviation of bore roller celerity (m/s);
$\overline{U}$	average bore roller celerity (m/s);
U_{mean}	temporal mean bore roller celerity (m/s);
V	flow velocity (m/s) positive downstream;
V_1	initial cross-sectional averaged flow velocity (m/s) immediately prior to the tidal bore passage;
X	instantaneous roller toe position (m);
X'	standard deviation of roller toe position (m);
X_{median}	cross-sectional median roller toe position (m);
x	longitudinal distance (m) positive downstream;

y	transverse distance (m) positive towards the right sidewall;
Z	instantaneous roller toe elevation (m);
Z'	standard deviation of roller toe elevation (m);
Z_{median}	median roller toe elevation (m);
z	vertical distance (m) positive upwards;
η	water surface elevation (m);
η'	standard deviation of water surface elevation (m);
θ	angle between channel bed slope and horizontal;

Subscript

mean	temporal mean value;
median	cross-sectional median value;
toe	roller toe property;
1	initial flow property immediately prior to the tidal bore passage;
2	conjugate flow property immediately after the tidal bore passage;
10	first decile;
25	first quartile;
75	third quartile;
90	ninth decile;

Abbreviations

ADM	acoustic displacement meter;
dSLR	digital single-lens reflex (camera);
fps	frames per second;
Std	standard deviation;
s	second.

Notes

All times are expressed in local times using the local time zone.

1. INTRODUCTION

A sudden increase in flow depth, e.g. caused by a sudden closure of a downstream regulation gate, induces a positive surge or compression wave (HENDERSON 1966, BRYSON 1969, LIGGETT 1994). In an estuary, a tidal bore is a positive surge generated by the early flood tide propagating upstream into a narrow funnelled channel under large tidal ranges (TRICKER 1965, CHANSON 2011). After formation, the bore may be analysed as a hydraulic jump in translation (RAYLEIGH 1908, LIGHTHILL 1978). The shape of the surge is a function of its Froude number Fr_1 (MONTES 1998, CHANSON 2012):

$$Fr_1 = \frac{V_1 + \overline{U}}{\sqrt{g \times \frac{A_1}{B_1}}} \quad (1\text{-}1)$$

where V_1 is the initial flow velocity positive downstream, $\overline{U}$ is the bore celerity positive upstream, g is the gravity acceleration, A_1 is the initial flow cross-section area and B_1 is the initial free-surface width (Fig. 1-1). An undular surge is observed for $Fr_1 < 1.3$ to 1.5. For $Fr_1 > 1.4$ to 1.6, the leading edge of the bore is characterised by a breaking roller. Figure 1-2 presents photographs of breaking tidal bores. The bore roller is characterised by a sudden increase in water depth, a highly turbulent flow with large-scale vortical structures, some kinetic energy dissipation, a two-phase air-water flow region and strong turbulence interactions with the free surface associated with splashes and droplet ejections. For a stationary hydraulic jump, $\overline{U} = 0$ and the inflow Froude number becomes: $Fr_1 = V_1/(g \times A_1/B_1)^{1/2}$ (CHANSON 2012).

Herein a physical investigation was conducted in laboratory with a focus on the bore roller properties. New experiments were conducted in a large size facility. The observations included a series of video observations of propagating breaking bores to characterise the roller toe perimeter, the bore front celerity and their fluctuations, as well as some preliminary unsteady air entrainment measurements in the bore roller using a dual-tip phase-detection probe.

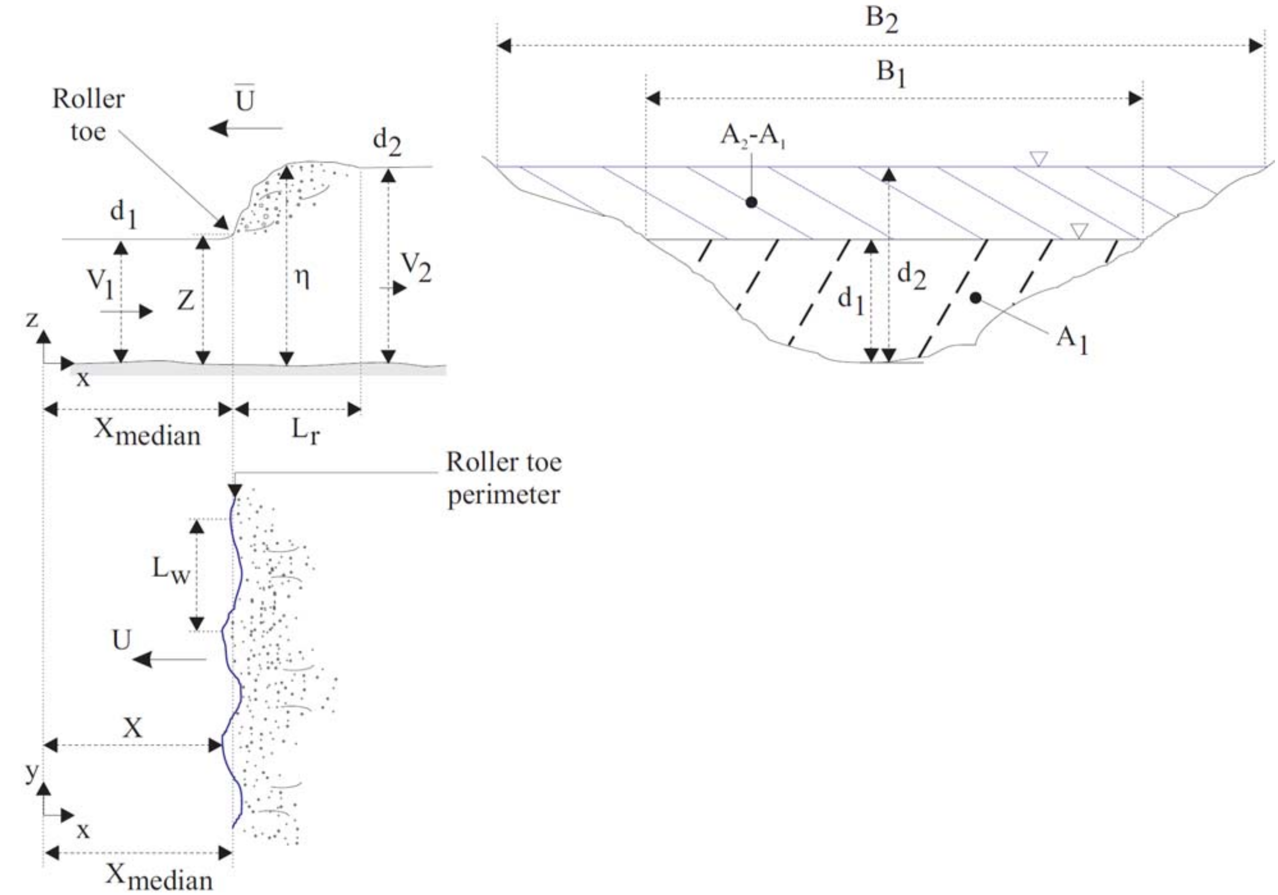


Fig. 1-1 - Definition sketch of a tidal bore propagating in an irregular cross-section channel

(A, Left) Tidal bore of the Sélune River at Pointe-du-Grouin-du-Sud, France on 19 October 2008 at 09:25 - Bore propagation from right to left

(B, Right) Breaking tidal bore of the Qiantang River at Laoyanchang, China on 6 September 2013 at 13:10 - Bore propagation from left to right

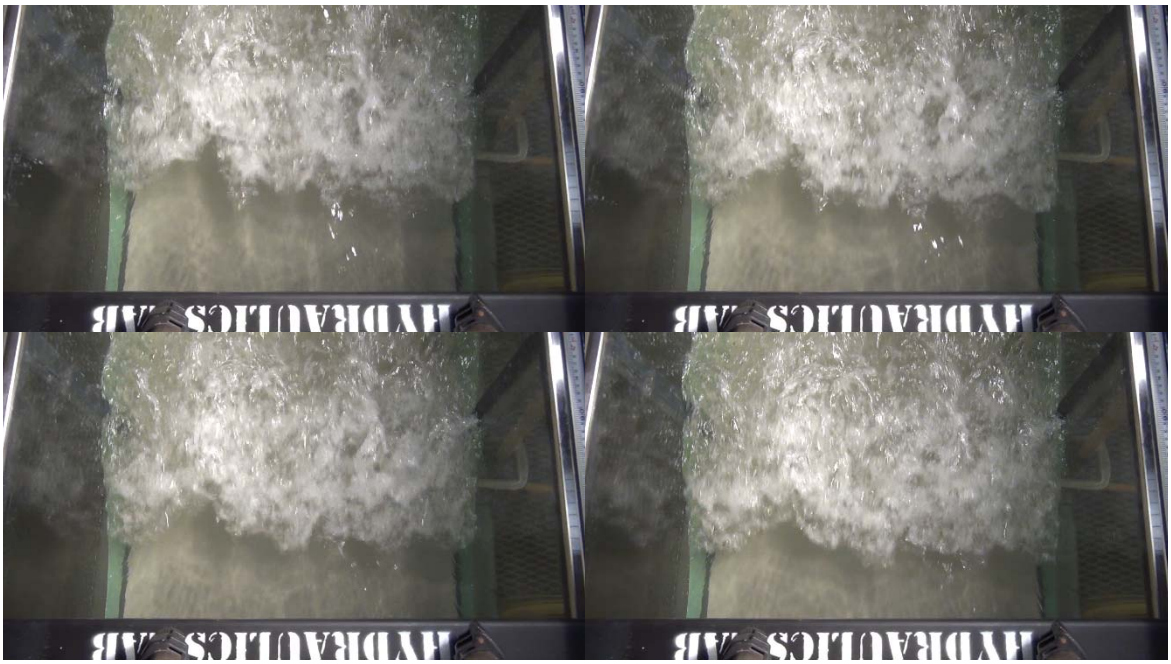
(C) Tidal bore of the Garonne River at Podensac, France on 24 August 2013 about 08:10 - Looking downstream at the incoming bore front

Fig. 1-2 - Photographs of tidal bores with breaking roller (Photographs Hubert CHANSON)

2. EXPERIMENTAL FACILITY AND SETUP

New experiments were conducted in a 19 m long 0.7 m wide tilting channel, made of glass sidewalls and smooth PVC bed ([1]) (Fig. 2-1). The bed slope was horizontal herein (S_o = 0) and the channel ended with a free overfall. The initially steady flow was supplied by a constant head reservoir, delivered into an upstream intake channel and led to the glass sidewalled test section through a series of flow straighteners followed by a smooth bed and sidewall convergent. A fast-closing tainter gate was located next to the test section's downstream end (x = 18.1 m), where x is the horizontal distance from the upstream end of the flume. Figure 2-2 shows a photograph of the gate and a dimensioned sketch.

(A) Looking downstream: left: with camera in foreground; right: advancing bore



(B) Photographic sequence of views in elevation with a time interval of 0.02 s photographs (Run 2a) (from left to right, top to bottom) - Bore propagation from top to bottom

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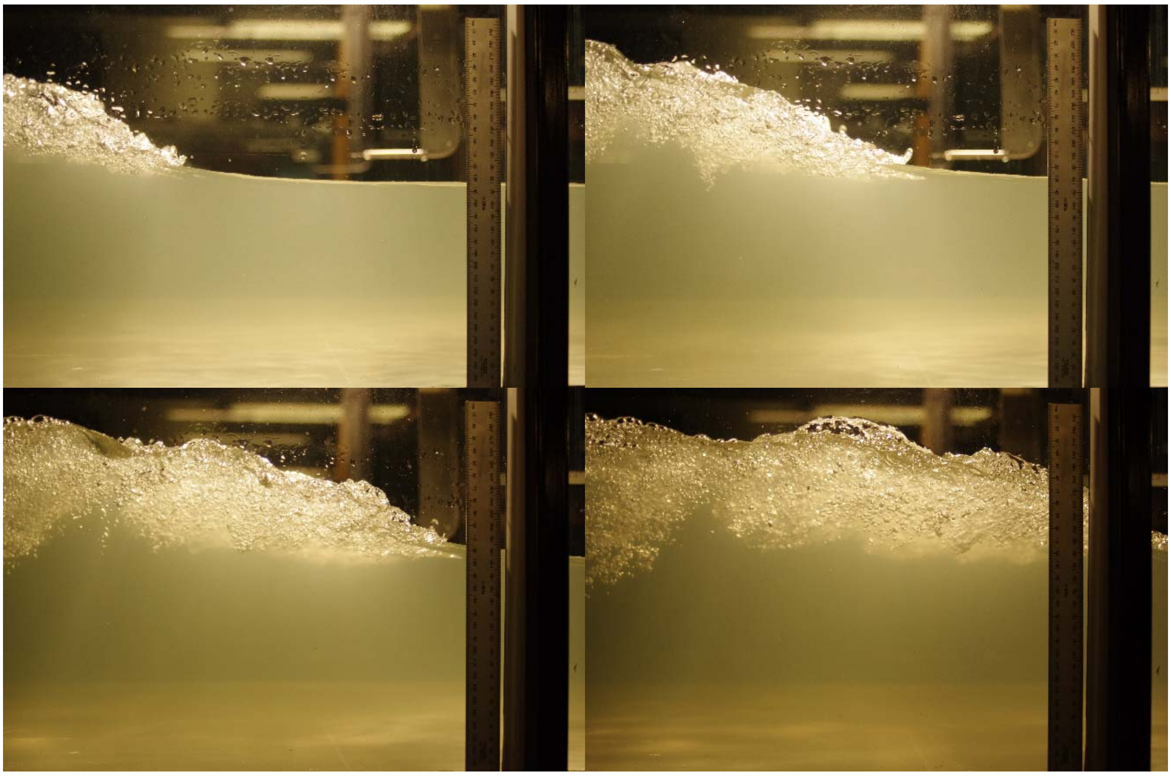
[1] The hydraulic roughness of the channel was tested in steady gradually-varied flows and the equivalent Darcy friction factor was f = 0.016 on average, corresponding to an equivalent sand roughness height k_s = 0.1 mm based upon the Colebrook-White formula (COLEBROOK 1939).



(C) Photographic side views of the bore roller with a time interval of 0.12 s between photographs (Run 3, d^1 = 0.160 m) - Bore propagation from left to right - Note the phase-detection probe on the top right; for scale, the vertical graduated ruler (on right) is 300 mm long

Fig. 2-1 - Experimental facility in operation

The video observations were conducted using a HD video camera Sony^{TM} HDR-XR160, operating at 25 fps or 50 fps, with a resolution of 1920×1080 pixels, and a digital camera Casio^{TM} Exlim EX-10, set at 120 fps (640×480 pixels), 240 fps (512×384 pixels) or 480 fps (224×160 pixels). The video camera was mounted vertically looking down across the channel width at about x = 6.6 to 6.7 m (Sony^{TM} HDR-XR160) and x = 9.2 m (Casio^{TM} Exlim EX-10). Figure 2-1B illustrates a typical extract of video movies. A total of 15 videos were recorded under the same flow conditions, with 5 at 25 fps, 5 at 50 fps, 2 at 120 fps, 2 at 240 fps and 1 at 480 fps. A two-bulb fluorescent light was used to achieve a fast shutter speed. Photographic sequences in high-speed continuously shooting mode (8.3 fps) were taken through the sidewalls to capture the instantaneous free-surface profiles during the bore front passage (Fig 2-1C). The dSLR camera was a Pentax^{TM} K-3 with Carl Zeiss^{TM} Distagon 28 mm f2 lens, producing photographs with a low degree (< 1%) of barrel distortion. Both the video movies and dSLR photographs were analysed manually to guarantee maximum reliability of the data.

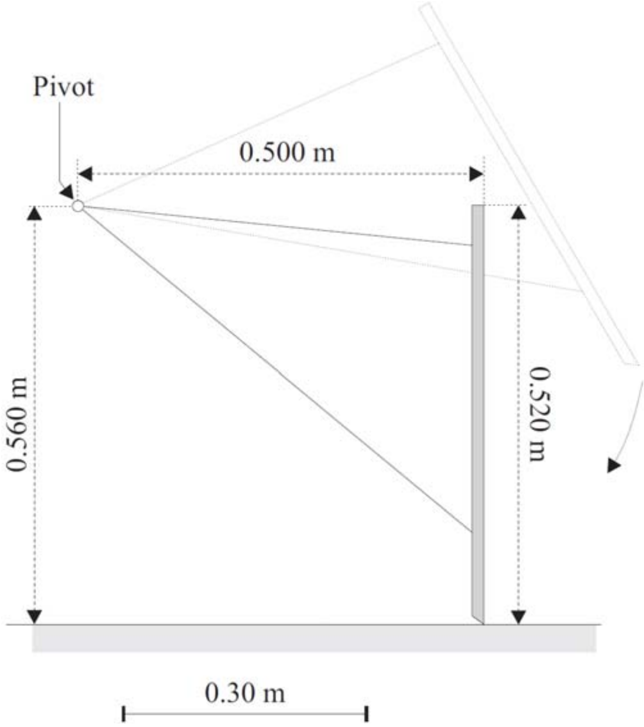
During the air entrainment experiments, a dual-tip phase-detection conductivity probe was used to detect the bubbles entrained in the breaking roller. The sensor size was 0.25 mm and the longitudinal distance between the two tips was 6.5 mm. The dual-tip probe was excited by an electronic system (Ref. UQ82.518) designed with a response time of less than 10 μs. The vertical elevation of the probe was controlled by a Mitutoyo™ digimatic scale unit with an accuracy of 0.01 mm. The probe sampling rate was 40 kHz per sensor and the probe signal output was processed manually. The conductivity probe was placed at x = 7.1 m facing downstream and the measurements were performed at several elevations, typically above the initial water level. The data at different vertical elevations were synchronised using sideview photographs taken simultaneously, yielding the median free-surface elevations as a function of x-X, where X is the instantaneous roller toe longitudinal location.

For all experiments, the discharge was 0.085 m^3/s. The breaking bores were generated by the complete fast closure of the tainter gate (Fig. 2-2) and the bore propagated upstream against the initially-steady flow (Fig. 2-1). Table 2-1 summarises the experimental flow conditions.

Table 2-1 - Experimental flow conditions with breaking bores

Reference	Run	S_o	B (m)	Q (m^3/s)	d_1 (m)	V_1 (m/s)	$\overline{U}$ (m/s)	Fr_1	Instrumentation	Date
Present study	1	0	0.70	0.085	0.160	0.76	0.99	1.40	Video (25 fps) at x = 6.6 m	03/07/2014
	2a			0.085	0.146	0.83	0.95	1.49	Video (50 fps) at x = 6.6 m	09/07/2014
	2b			0.085	0.146	0.83	0.95	1.49	Phase-detection probe at x = 7.1 m	09/07/2014
	3			0.085	0.160	0.76	0.97	1.38	Phase-detection probe at x = 7.1 m	17/07/2014
	4			0.085	0.165	0.74	0.90	1.33	Video (120, 240, 480 fps) at x = 9.2 m	20/8/2014
YEH and MOK		0	0.61	0	0.060	0	--	1.35	Water sensors and	
(1990)					0.060	0	--	1.52	argon-ion laser sheet	
					0.040	0	--	1.72		
					0.040	0	--	1.93		
					0.40	0	--	2.07		
CHANSON (2010)	091103	0	0.50	0.0261	0.100	0.52	0.82	1.36	Hydrophone Dolphin Ear	3/11/2009
	091110b			0.0435	0.138	0.63	0.95	1.36		10/11/2009
	091125			0.0563	0.116	0.97	0.83	1.68		25/11/09
DOCHERTY and	Smooth	0	0.50	0.050	0.117	0.85	0.847	1.59	ADV, acoustic	5/01/2010
CHANSON (2012)	Gravel	0.002	0.50	0.050	0.127	0.79	0.885	1.50	displacement meters	19/01/2010
TOI and	Smooth	0.0035	0.50	0.025	0.052	0.96	0.53	2.10	ADV, acoustic	15/12/2010
CHANSON (2013)	PVC				0.051	0.98	0.46	2.02	displacement meters	21/12/2010
					0.052	0.96	0.40	1.91		15/12/2010
					0.051	0.98	0.26	1.74		21/12/2010

Notes: B: channel width; d_1: initial water depth recorded at x = 7.1 m (Present study); Fr_1: bore Froude number: $Fr_1 = (\overline{U}+V_1)/(g \times d_1)^{1/2}$; S_o: bed slope; $\overline{U}$: cross-sectional time-averaged bore celerity recorded at x = 7.1 m (Present study); V_1: initial flow velocity recorded at x = 7.1 m (Present study); x: longitudinal distance from upstream end of glass sidewalled channel; (--): information not available.



(A, Left) Dimensioned sketch of tainter gate

(B, Right) Photograph taken immediately after gate closure (Q = 0.10 m^3/s, d_1 = 0.157 m, shutter speed: 1/1,000 s)

Fig. 2-2 - Details of the tainter gate - Initially steady flow direction from right to left

3. RESULTS

3.1 ROLLER TOE PERIMETER

In hydraulic jumps with breaking roller and in breaking bores, the roller toe is a flow singularity where air is entrapped and vorticity is generated (HORNUNG et al. 1995). It is also called breaker toe (BROCCHINI and PEREGRINE 2001) and corresponds to the position for base of a breaker, at the boundary between smooth and turbulent flow at the water surface, see the examples in Figures 1-2 and 2-1. View in elevation, the roller toe formed a continuous line, herein called the roller toe perimeter (Fig. 1-1). The shape of the roller toe perimeter and its evolution with time were investigated in details. For Runs 1, 2a and 4 (Table 2-1), the video movies were digitalised frame-by-frame to document the instantaneous perimeter of the roller toe during its upstream propagation and its variations with time. The data highlighted the broad range of instantaneous shapes of the roller toe perimeter. Figure 3-1 shows typical transverse profiles of the roller toe perimeter, where x = X is the instantaneous toe location at a transverse distance y with y = 0 at the left side wall. Altogether the roller toe was quasi two-dimensional on average, although its shape changed rapidly with both longitudinal and transverse directions, as well as with time. The data showed some backshifts of roller toe location with time, indicating that the toe occasionally shifted backwards for a very short time with a negative instantaneous celerity (e.g. Fig. 3-1, t ≈ 0.06 s).

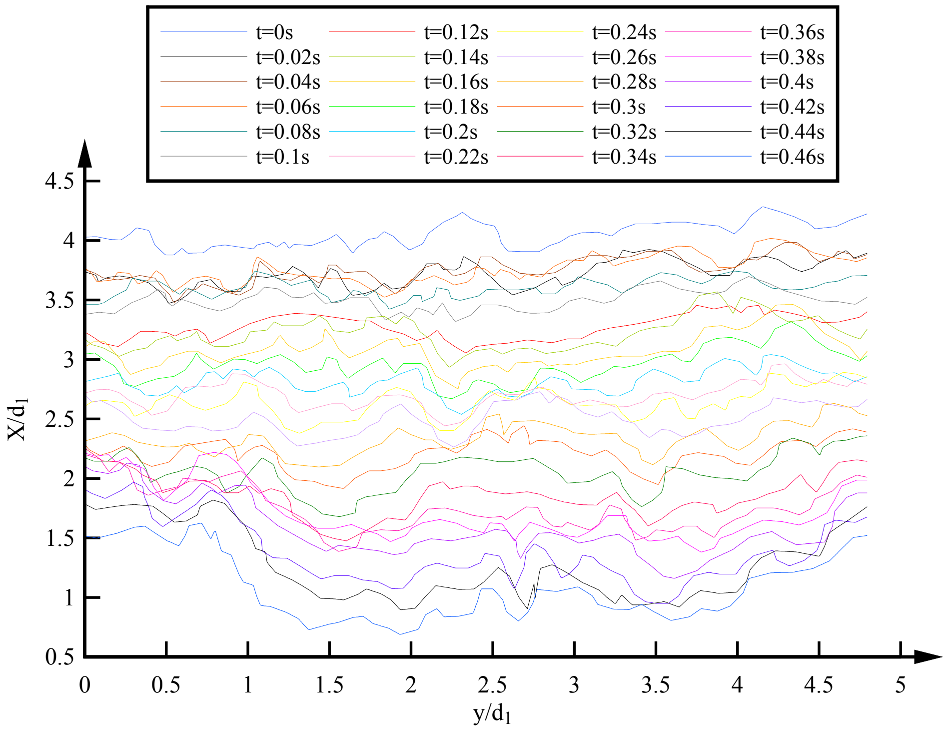


Fig. 3-1 - Instantaneous roller toe perimeter as function of time (Run 2a) - Bore propagation from top to bottom

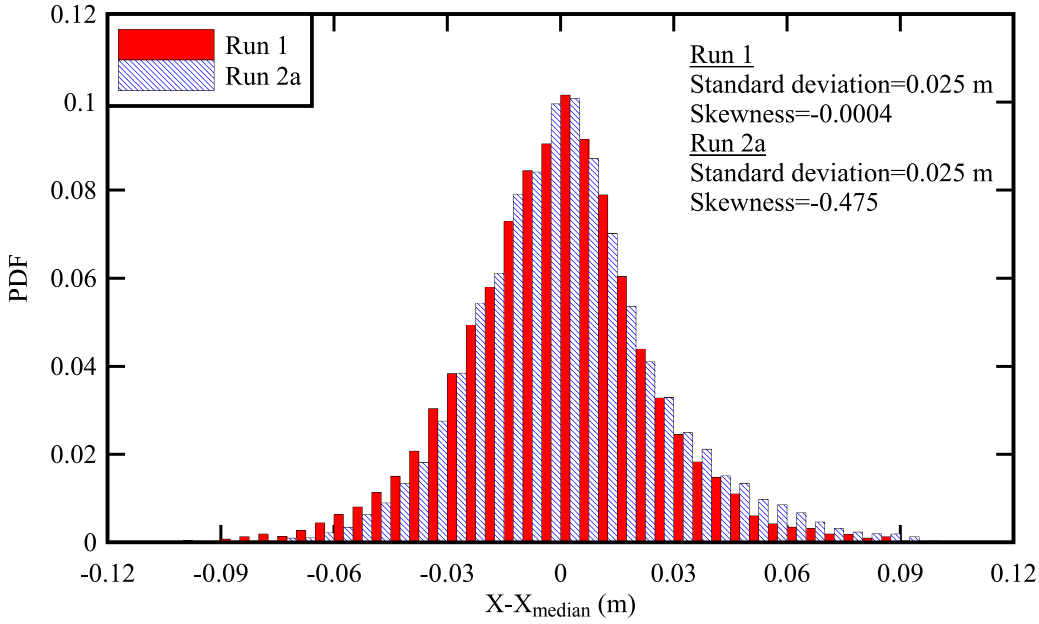


Fig. 3-2 - Probability distribution functions of longitudinal fluctuations of the roller toe about its median (Run 1, 25 fps & Run 2a, 50 fps)

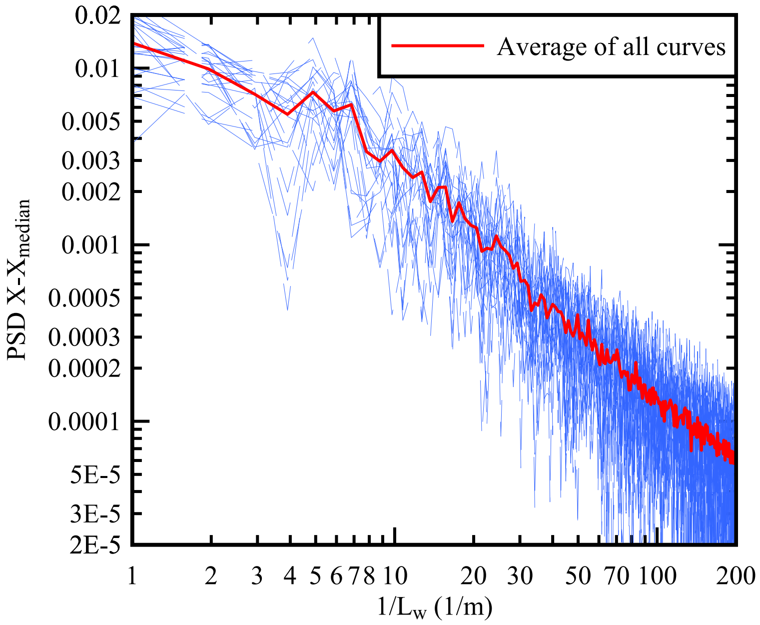


Fig. 3-3 - Power spectral density function of the transverse fluctuations in roller toe perimeter about its median position - Run 2a, single video movie, 50 fps

The deviations of the roller toe perimeter about the instantaneous cross-sectional median position X_{median} were calculated, and the results indicated some quasi-periodic fluctuation of the toe perimeter in the transverse direction. Some typical probability distribution functions of transverse perimeter fluctuation ($X-X_{median}$) are shown in Figure 3-2. The data sets exhibited a quasi-normal distribution and the results were basically independent of the movie frame rate, yielding $(X-X_{median})'/d_1 = 0.145$ on average at a given time.

The transverse profile of the roller toe perimeter showed some pseudo-periodic shape (Fig. 2-1B & 3-1), indicating the existence of non-linear structures, streamwise vortices and streaks. The present observations suggested a phenomenon very similar to that observed in plane mixing layers and wall jets (BERNAL and ROSHKO 1986, LEVIN et al. 2005). At a fixed time, the fluctuations of toe perimeter location around its median were analysed in terms of relevant transverse wave lengths L_w, see definition in Figure 1-1. Figure 3-3 shows typical data, with the average curve highlighting two characteristic peaks corresponding to transverse wave lengths of 0.2 m and 0.146 m, respectively. For the entire data set, the predominant wave length was $L_w \sim 0.2$ m (i.e. $L_w/d_1 \sim 1.2$).

Discussion: comparison with prototype observations and stationary hydraulic jumps

On 6 September 2013, the second author observed the breaking bore of the Qiantang River in the northern channel near Xinchang (China). The bore roller was nearly straight and over 200 m wide, as it advanced towards the photographer (Fig. 3-4A). A number of high-resolution photographs ([2]) were recorded and analysed. The data are presented in terms of the roller toe perimeter in Figure 3-4B and 3-4C. The instantaneous roller toe position fluctuated about the cross-section median rapidly with both time and transverse direction. The dimensionless standard deviation $(X-X_{median})'/d_1$ was about 0.13 for the Qiantang River bore, and the present laboratory observations: $(X-X_{median})'/d_1 = 0.145$ compared well with the field observations. In the Qiantang River, the transverse variations of instantaneous toe perimeter presented some pseudo-periodic fluctuations, with a range of transverse wave lengths within $0.7 < L_w/d_1 < 25$. The two dominant dimensionless wave length ranges were $L_w/d_1 \sim 1$ and 5-10.

For comparison, ZHANG et al. (2013) reported transverse wave lengths of roller toe perimeters in stationary hydraulic jumps with wave lengths L_w/B between 2/3 and 2, i.e. $13 < L_w/d_1 < 40$ for $Fr_1 = 6$. In the same study, a photograph suggested large streamwise vortices in the shear layer with wave lengths about 1 to $10 \times d_1$. Assuming a ratio of transverse to longitudinal wave lengths about 2/3 (BERNAL and ROSHKO 1986), this would correspond to dimensionless transverse wave lengths L_w/d_1 between 0.7 and 7. For completeness, CHANSON (2007) observed transverse integral turbulent length scales about $0.3 \times d_1$ in the developing air-water shear layer of stationary hydraulic jumps.

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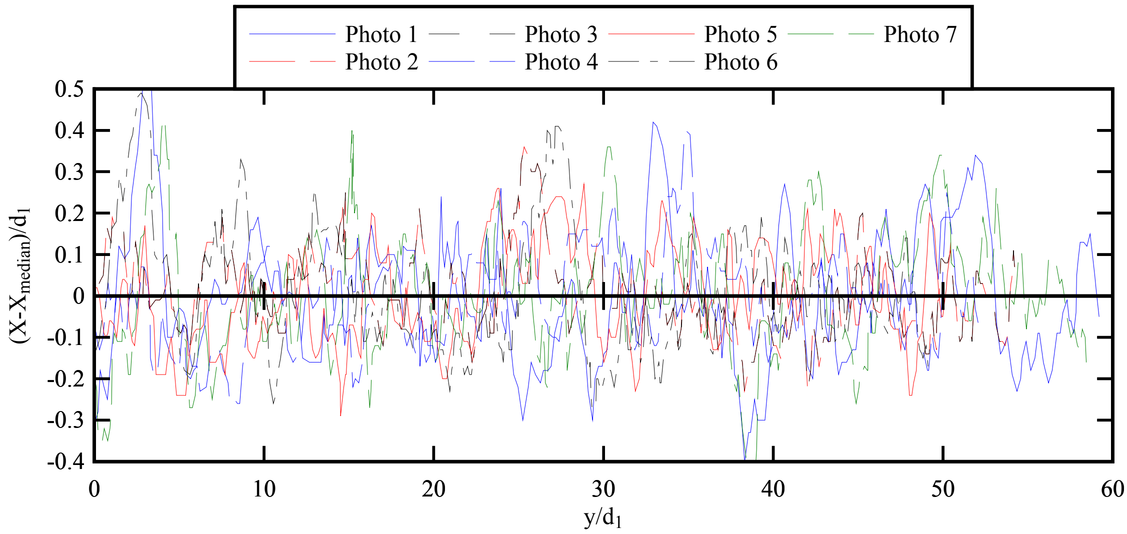
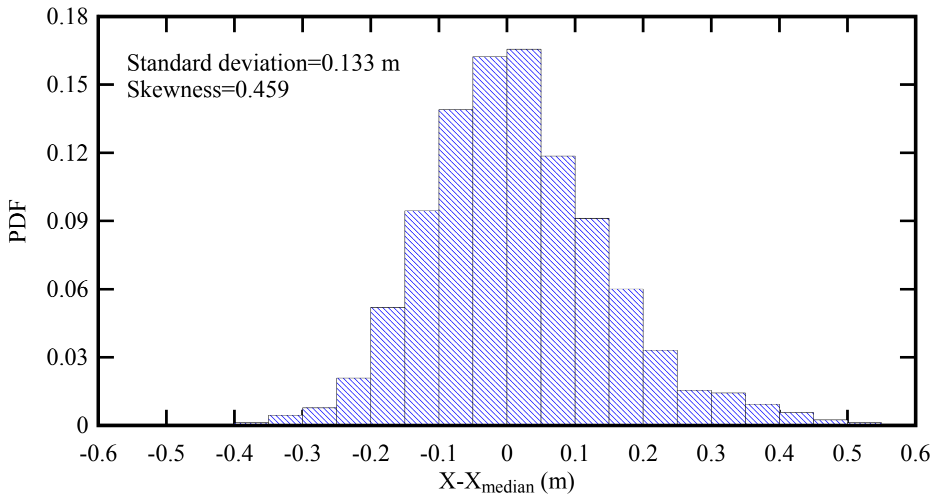
[2] Taken using a dSLR camera Pentax™ K-7 with Voigtlander™ Nokton 58 mm f1.4 lens, producing photographs with a very low degree (< 0.3%) of barrel distortion.

(A) Photograph of the advancing roller looking downstream (Photograph Hubert CHANSON)



(B) Instantaneous roller toe perimeter deviation about the instantaneous cross-section median



(C) Probability distribution function of longitudinal fluctuations of the roller toe about its median

Fig. 3-4 - Breaking bore of the Qiantang River in the northern channel downstream of Xinchang, China on 6 September 2013 at 11:50 - $d_1 \sim 1$ m, $\overline{U} \sim 3.6$ m/s, $Fr_1 \sim 2.1$

3.2 LONGITUDINAL ROLLER PROFILE

Some typical instantaneous roller surface profiles are shown in Figure 3-5, while Figure 2-1C presents some high-shutter speed photographs. All the data highlighted the rapid fluctuations in roller surface elevations as well as the rapid changes in longitudinal roller profiles with time. The instantaneous free-surface fluctuations were herein described in terms of the differences between 9th and 1st deciles (d_{90}-d_{10}) and third and first quartiles (d_{75}-d_{25}). For a Gaussian distribution of the data set about its mean, (d_{90}-d_{10}) and (d_{75}-d_{25}) would be equal respectively to 2.6 and 1.3 times the standard deviation (SPIEGEL 1972). The present data indicated a maximum in free-surface fluctuations in the first half of the roller (Fig. 3-5). The present results $(d_{75}\text{-}d_{25})_{max}$ are reported in Figure 3-6 and compared with previous studies of maximum turbulent fluctuations η'_{max} of the free-surface in stationary hydraulic jumps. Some re-analysed breaking tidal bore data are also included (DOCHERTY and CHANSON 2012, TOI and CHANSON 2013). All the data highlighted free-surface fluctuations comparable between breaking bores and stationary hydraulic jumps for some comparable Froude number (Fig. 3-6). This is believed to be the first successful comparison of that kind.

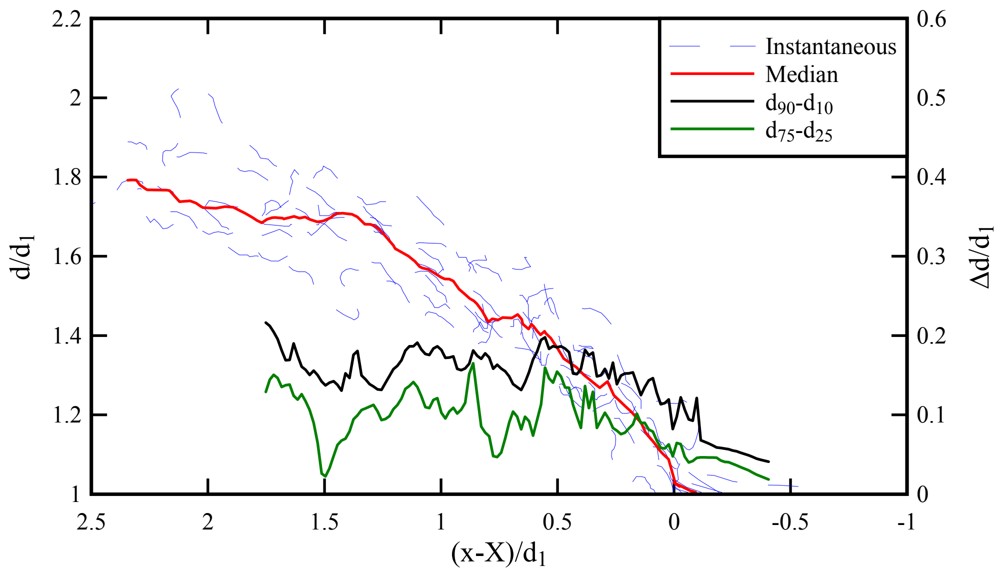
The visual observations showed that the free-surface elevation first rose slowly immediately prior to the roller, for Froude numbers less than 2, seen in Figures 2-1C and 3-5. Such an upward streamline curvature derived from theoretical considerations, namely the integral balances of linear momentum, in both horizontal and vertical directions, and of angular momentum (VALIANI 1987). This gradual rise in free-surface ahead of the turbulent roller was previously observed (HORNUNG et al. 1995, KOCH and CHANSON 2009). Immediately after the roller toe, there was a marked discontinuity in the surface slope and curvature, and the bore roller induced a sharp rise in water depth linked with the flow singularity (Fig. 3-5). The vertical elevation Z of the roller toe was recorded and the data were compared with re-analysed breaking tidal bore data (Table 3-1). The results are presented in Figure 3-7. Figure 3-7A shows probability distributions of toe elevation about its median. Figure 3-7B regroups the dimensionless median toe elevation Z_{median}/d_1 and toe elevation fluctuations $(Z_{75}-Z_{25})/d_1$ data as functions of the Froude number, where Z_{75} and Z_{25} are the third and first quartiles respectively. Despite some difference in measurement techniques and boundary flow conditions, all the data indicated a decrease in roller toe elevation with increasing Froude number. The data were best correlated by:

$$\frac{Z_{median}}{d_1} - 1 = 0.1854 \times \exp(-3.52 \times (Fr_1 - 1.3)) \qquad (3\text{-}1)$$

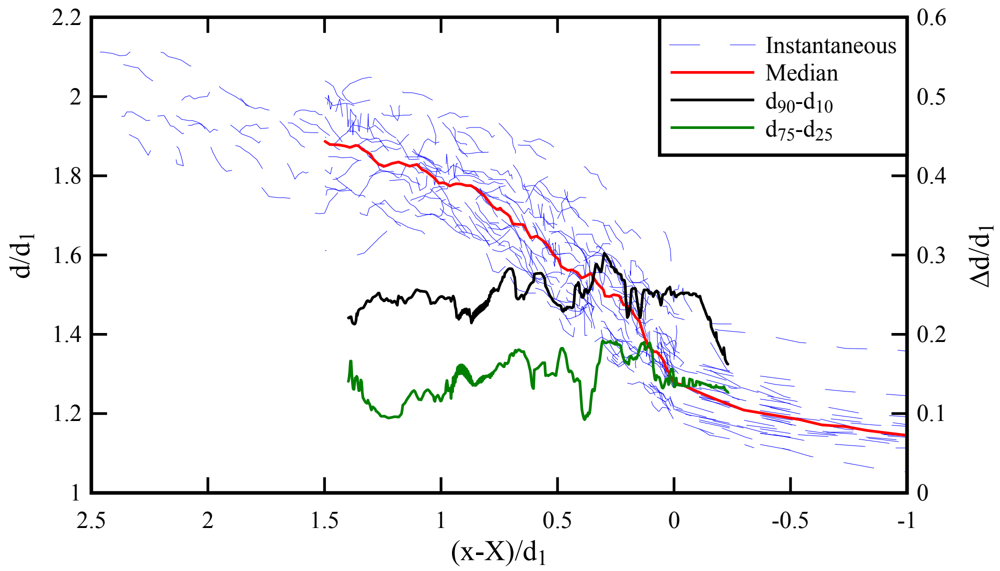
with a normalised correlation coefficient of 0.823 and a standard error of 0.033 (Fig. 3-7B). The fluctuations in vertical elevation of roller toe showed also a decreasing trend with increasing Froude number. The results are shown in Figure 3-7B in terms of the difference between third and first quartiles. The data were correlated by:

$$\frac{Z_{75} - Z_{25}}{d_1} = 0.105 \times \exp(-1.99 \times (Fr_1 - 1.3)) \tag{3-2}$$

with a normalised correlation coefficient of 0.835 and a standard error of 0.0168. Both Equations (3-1) and (3-2) are compared with breaking bore data in Figure 3-7B, and the tabular data are reported in Table 3-1.



(A) Run 2b, $Fr_1 = 1.5$, $\overline{U} = 0.95$ m/s, $d_1 = 0.146$ m



(B) Run 3, $Fr_1 = 1.4$, $\overline{U} = 0.97$ m/s, $d_1 = 0.160$ m

Fig. 3-5 - Longitudinal roller profile of breaking bores - Instantaneous and median profiles, and free-surface fluctuations

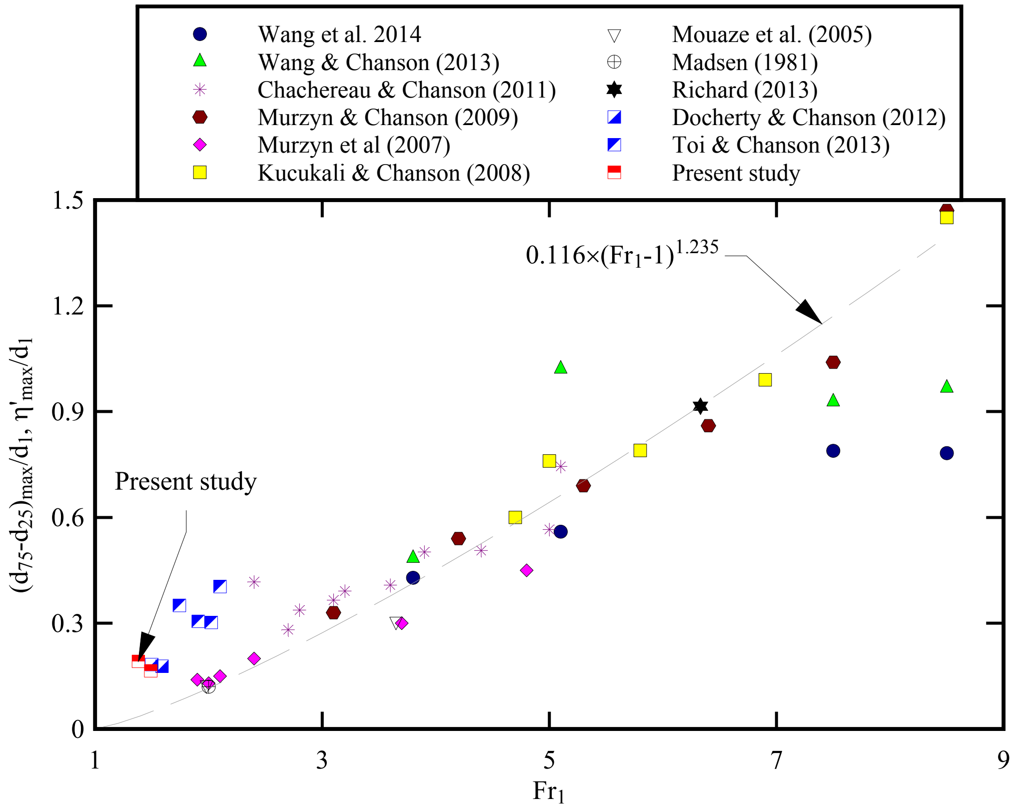
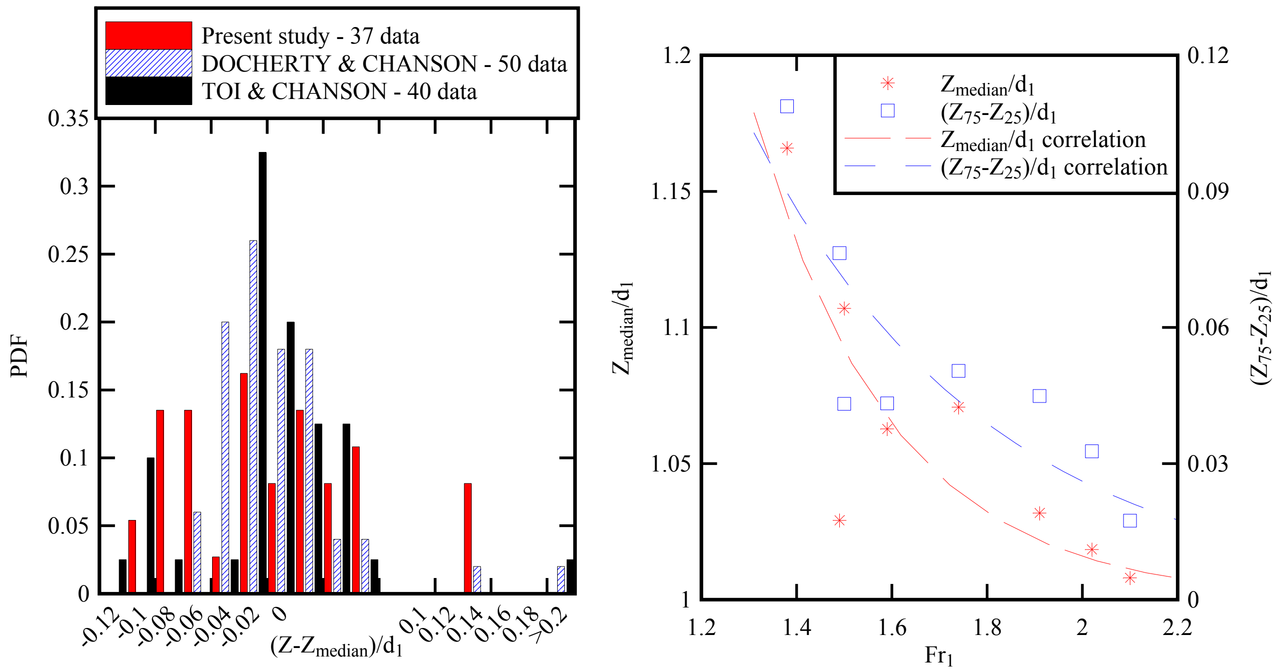


Fig. 3-6 - Maximum free-surface fluctuations in breaking bores and hydraulic jumps as functions of Froude number - Tidal bore data: $(d_{75}-d_{25})_{max}/d_1$, DOCHERTY and CHANSON (2012), TOI and CHANSON (2013), Present study (white and blue squares) - Hydraulic jump data η'_{max}/d_1: theoretical calculations (RICHARD 2013), experimental data (MADSEN 1981, MOUAZE et al. 2005, MURZYN et al. 2007, KUCUKALI and CHANSON 2008, MURZYN and CHANSON 2009, CHACHEREAU and CHANSON 2011a, WANG and CHANSON 2013, WANG et al. 2014)

Table 3-1 - Experimental observations of roller toe characteristics in breaking tidal bores

Reference	Bed	d_1 (m)	Fr_1	Measurement technique	$\frac{(d_{75}-d_{25})_{max}}{d_1}$	$\frac{Z_{median}}{d_1}$	$\frac{Z_{75}-Z_{25}}{d_1}$	Nb of data ([a])
Present study	PVC	0.146	1.49	dSLR photography	0.165	1.029	0.076	8
		0.160	1.38	through sidewall	0.192	1.166	0.109	29
DOCHERTY and	PVC	0.117	1.59	ADM measurements	0.178	1.063	0.043	25
CHANSON (2012)	Gravel	0.127	1.50	on centreline	0.183	1.107	0.043	25
TOI and	PVC	0.052	2.10	ADM measurements	0.404	1.008	0.017	10
CHANSON (2013)		0.051	2.02	on centreline	0.302	1.018	0.033	10
		0.052	1.91		0.305	1.032	0.045	10
		0.051	1.74		0.350	1.071	0.050	10

Notes: ADM: acoustic displacement meter; Fr_1: bore Froude number; ([a]): number of roller toe vertical elevation samples.



(A, Left) Probability distribution functions of the roller toe elevation about its median

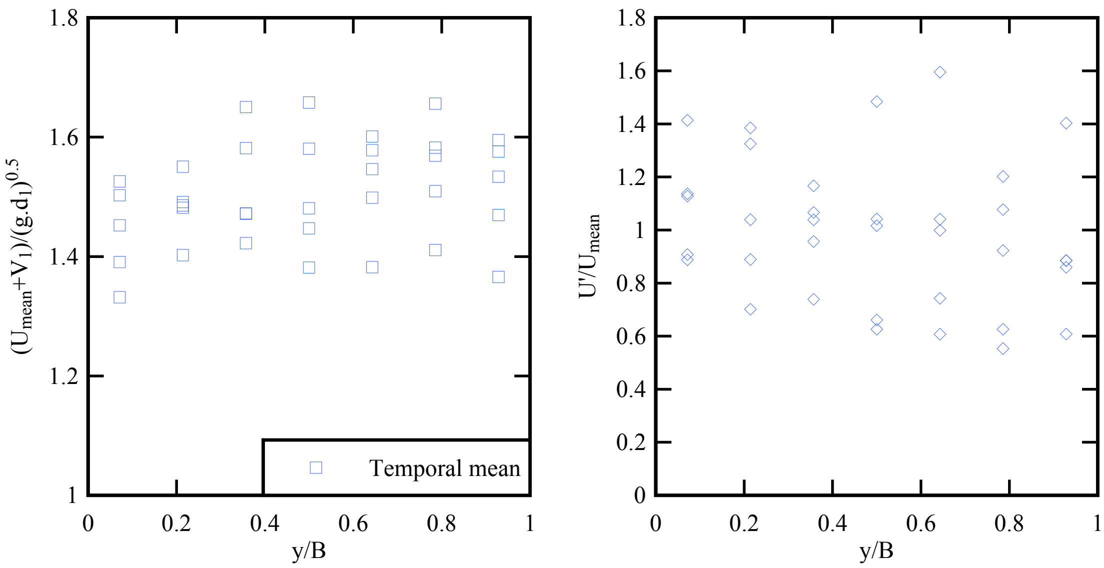
(B, Right) Median roller toe elevation and difference between third and first quartiles (DOCHERTY and CHANSON 2012, TOI and CHANSON 2013, Present data) - Comparison with Equations (3-1) and (3-2) respectively

Fig. 3-7 - Fluctuations in vertical elevations Z/d_1 of the roller toe - Comparison between Present data and re-analysed data (DOCHERTY and CHANSON 2012, TOI and CHANSON 2013)

The asymptotic limits of the data indicated two distinct trends. For $Fr_1 < 1.3$, the bore was undular and the roller disappeared. For $Fr_1 > 2$, the dimensionless roller toe elevation Z/d_1 tended to unity and the fluctuations in roller toe elevation tended to small values corresponding to the initial free-surface fluctuations. The upper limit $Z/d_1 = 1$ was consistent with breaking tidal bore observations (MOUAZE et al. 2010) and stationary hydraulic jump data (MADSEN 1981, MURZYN et al. 2007, CHACHEREAU and CHANSON 2011a) for $Fr_1 > 2$. In stationary hydraulic jumps, physical data showed $\eta_{toe}'/d_1 \approx 0.02$ for $Fr_1 = 2.0$ and 2.7 that corresponded to the upstream free-surface fluctuations (MADSEN 1981, CHACHEREAU and CHANSON 2011a).

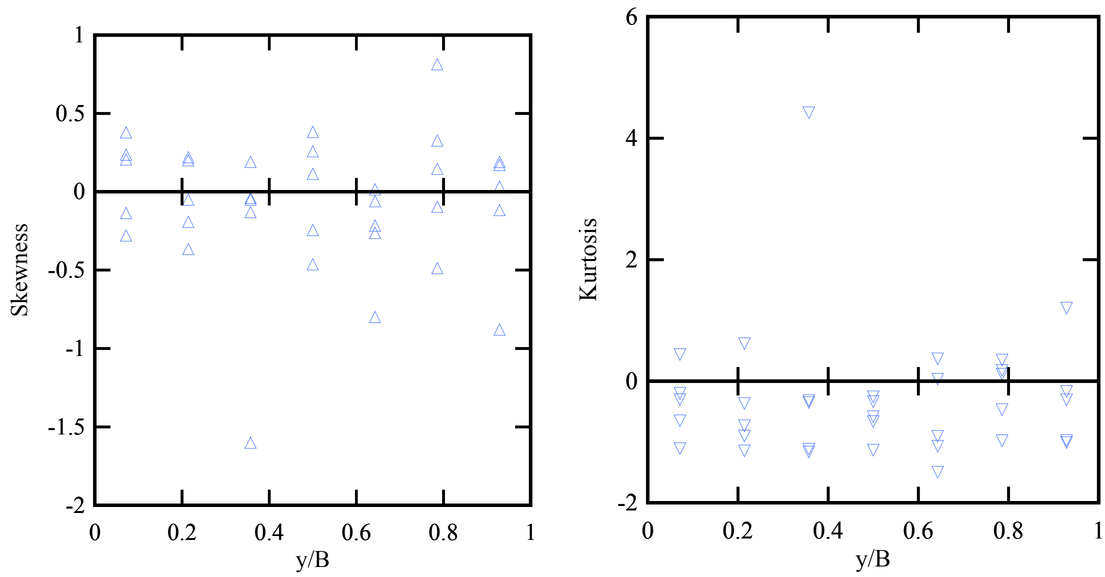
3.3 BORE ROLLER CELERITY

The bore roller celerity was calculated based upon the instantaneous roller toe positions. The channel width was divided into seven 0.1 m wide sub-sections, and the mean celerity of each individual sub-section was estimated as a function of time (Fig. 3-8). The statistical results are shown in Figure 3-8, including temporal mean, standard deviation, skewness and kurtosis, for all five video movies of Run 2a, where B is the channel width (B = 0.7 m). All the data indicated no obvious sidewall effect under the current experimental setup and flow conditions (Table 2-1). The results showed large fluctuations in bore celerity with the ratio of standard deviation to temporal mean U'/U_{mean} between 0.6 and 1.6, with an average of all data about 0.99 (Fig. 3-8B).



(A) Temporal mean celerity

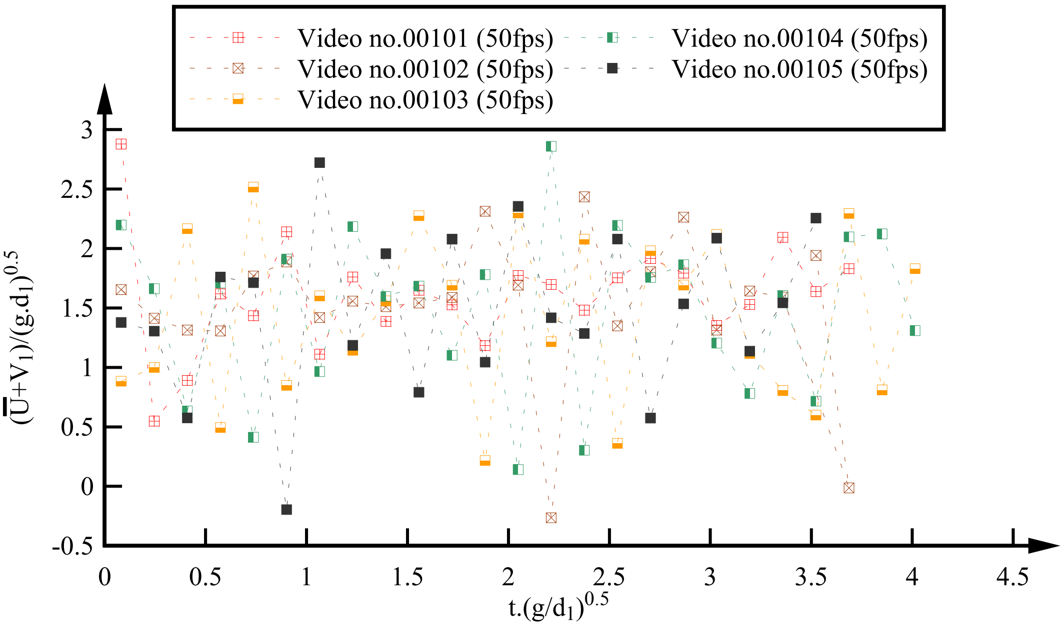
(B) Standard deviation



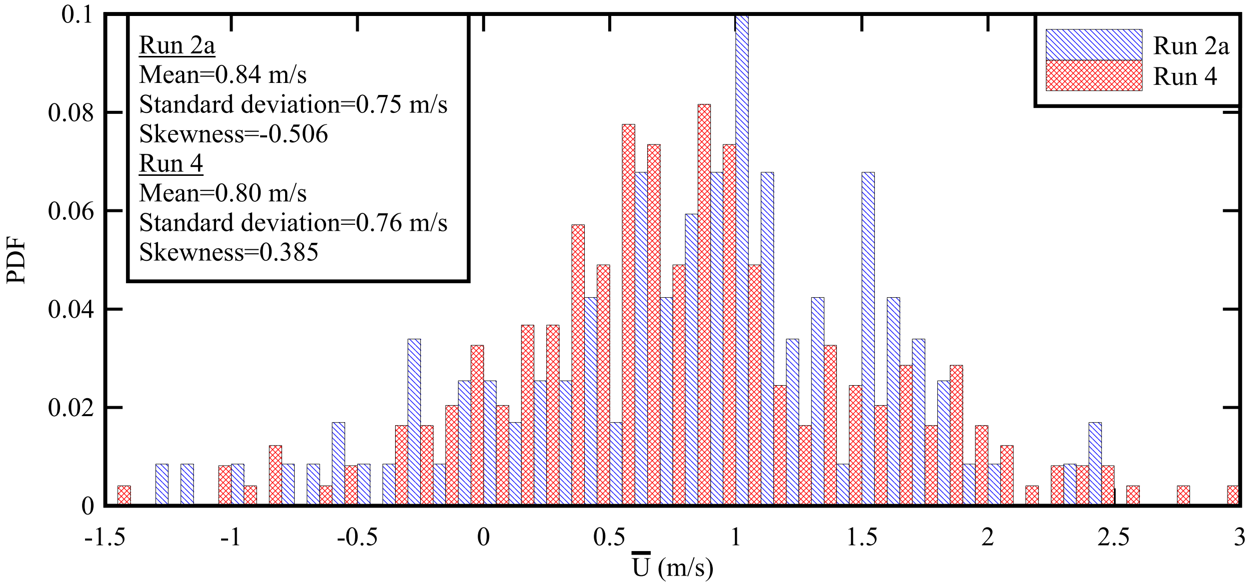
(C) Skewness

(D) Excess kurtosis

Fig. 3-8 - Transverse variations in roller toe celerity statistics (Run 2a, 50 fps) - each data point is an average over the video duration



(A) Dimensionless cross-sectional averaged celerity as a function of time (Run 2a, 50 fps, all five video movies)



(B) Probability distribution of cross-sectional mean celerity data (Combined data of Run 2a and Run 4)

Figure 3-9 - Cross-sectional averaged celerity $\overline{U}$ of the bore roller toe

The instantaneous cross-sectional averaged celerity $\overline{U}$ was derived from the median perimeter data of the bore roller. The mean results are reported in Table 2-1 (column 9) and some instantaneous data are presented in Figure 3-9. In Figure 3-9A, the instantaneous cross-sectional averaged celerity fluctuated rapidly with time about a median value of approximately $\overline{U} \approx 0.95$ m/s. YEH and MOK (1990) reported fluctuations in bore celerity during the propagation, although with lesser fluctuation magnitudes. The instantaneous celerity was not always positive, as seen for a few points in Figure 3-9A. These negative celerity data were consistent with some intermittent backshifts of the instantaneous roller toe perimeter discussed earlier. They might be related to the generation and advection of turbulent vortices in the roller as well as air bubble entrainment at the roller toe. Figure 3-9B presents further the probability distribution function of the celerity $\overline{U}$. The data showed typically similar outcomes for video frame rates of 50, 120, 240 and 480 fps ([3]).

3.4 UNSTEADY AIR BUBBLE ENTRAINMENT IN THE ROLLER

The instantaneous void fraction c is defined as 0 in the water and 1 in the air. Figure 3-10 presents the time variations of instantaneous void fraction c at different vertical elevation z/d_1, where t_{toe} is the time of passage of the bore roller toe. In Figure 3-10, the black lines correspond to the leading tip probe signal and the red lines to the trailing sensor signal. The data showed consistently that a substantial number of bubbles were entrapped between $1.25 < z/d_1 < 1.5$. No bubble was detected for $z/d_1 < 1.05$, while, above $z/d_1 > 1.5$, the air entrainment was more intermittent and the probe sensor interacted with the upper free-surface. The arrival time of the first bubble was delayed with increasing elevation as predicted by the longitudinal roller profile (Fig. 3-5). Lastly, in a few instances, the probe's leading tip was observed to detect the bore front after the trailing tip. This would be consistent with the bore roller toe moving with a negative celerity (section 3.3).

The bubble chord time data, recorded by both leading and trailing tips, showed increasing bubble chord times with increasing vertical elevations z/d_1. The largest number of bubbles were detected between $z/d_1 = 1.25$ and 1.5. Such a range of vertical elevations corresponded approximately to the impingement point (or roller toe) of the median bore front profile (Fig. 3-5).

The probability distribution functions of bubble chord times at all vertical elevations are plotted in Figure 3-11. Although the mean bubble chord time was 8.4 ms, the mode was about 2 ms and the data indicated a broad spectrum of chord times (Fig. 3-11). The present results were comparable to a previous study of stationary hydraulic jump for $Fr_1 = 3.1$ (CHACHEREAU and CHANSON 2011b). In that study, the large majority of detected bubbles had a chord time of 5 ms or less, with a mode about 1 ms. The present data showed also some large bubble chord times (> 20 ms), typically observed at higher elevations. There the air entrainment was more intermittent, the probe sensor interacted with the upper free-surface, and both surface waves and surface roughness influenced significantly the chord time distributions, with an increased percentage of large chords (TOOMBES and CHANSON 2007).

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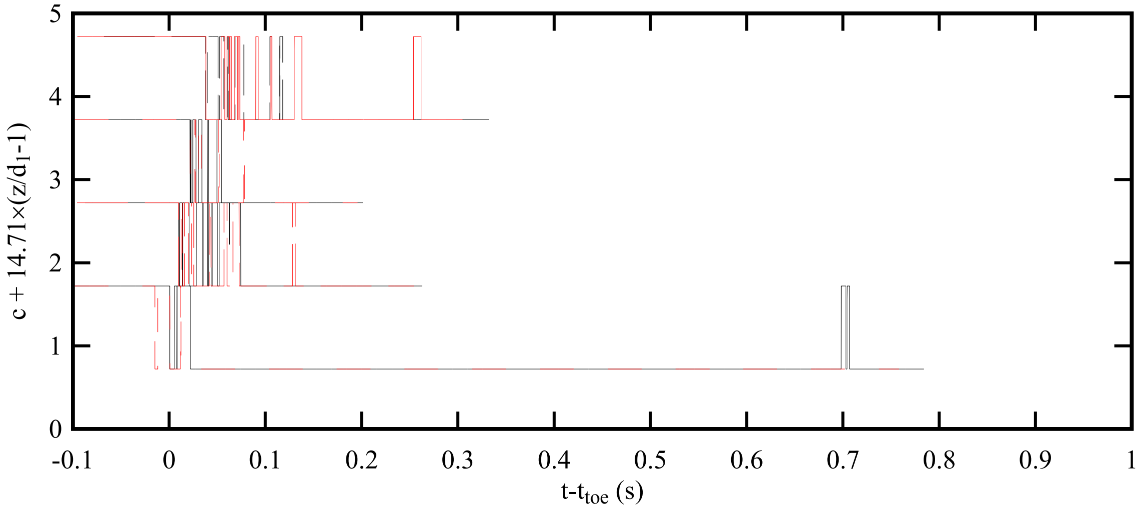
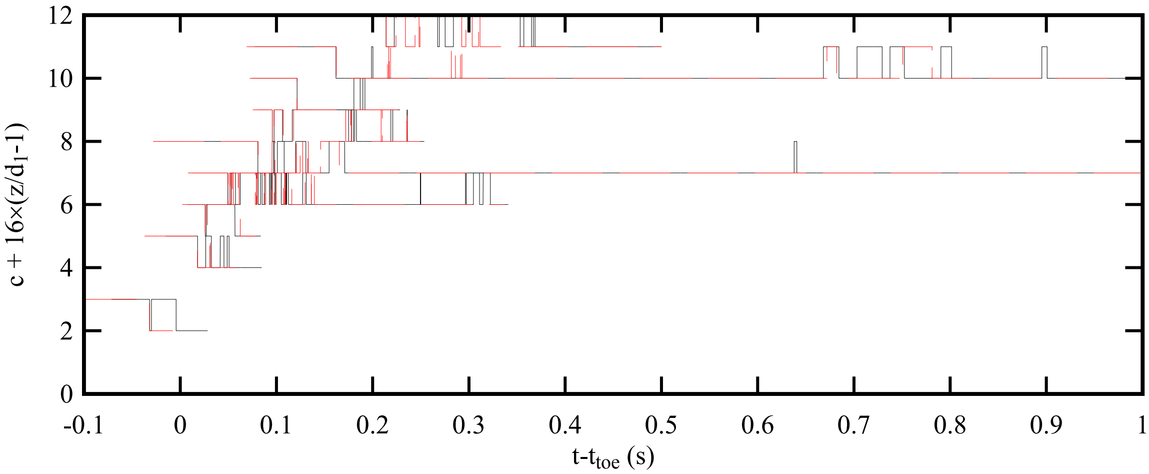
[3] The data at 25 fps tended to show some quantitative differences, likely caused by the sub-sampling.



(A) Run 2b



(B) Run 3

Figure 3-10 - Instantaneous void fraction c as a function of time ($t-t_{toe}$) at different vertical elevations above the initial flow depth - Black lines: leading tip signal; Red lines: trailing tip signal

High-shutter speed photographs showed a substantial number of bubbles with millimetric sizes: i.e., between 1 to 5 mm. Figure 3-12 presents such a high-shutter speed photograph in which the two black squares have 2 mm sides. One such square is seen in the inset (Fig. 3-12, Right). The photographic observations were comparable to acoustic bubble size distributions recorded in breaking tidal bores (Table 2-1) (CHANSON 2010). This study recorded "acoustic" bubble radii between 0.4 and 14 mm. Although bubble sizes are not strictly comparable to bubble radii, present observations (Fig. 2-1C & 3-11) were of the same order of magnitude as acoustic bubble radii.

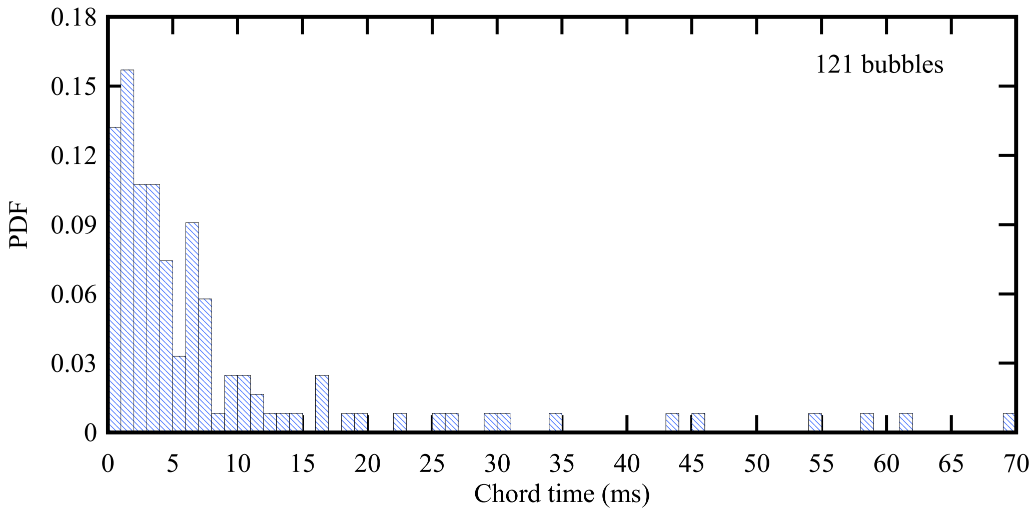


Fig. 3-11 - Probability distribution functions of bubble chord times (Runs 2b & 3, all detected bubbles)

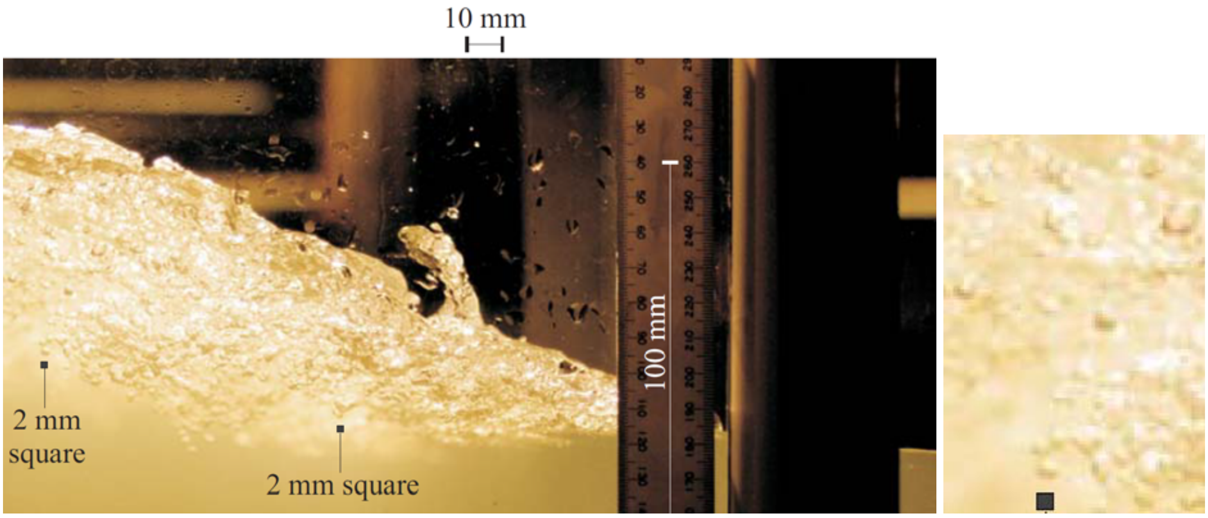


Fig. 3-12 - Side view of the bore roller and entrained bubbles (shutter speed: 1/4,000 s) (Run 3) - Bore propagation from left to right - Onset: details, with 2-mm black square for scale (bottom)

4. CONCLUSION

New experiments were conducted in a large-size laboratory facility to investigate breaking tidal bores and the upstream bore roller propagation. The experimental results highlighted several points.

(1) The propagation of the breaking bore roller toe was a highly turbulent process. While the transverse shape of the roller toe perimeter was quasi two-dimensional on average, the toe perimeter shape fluctuated rapidly with transverse distance and time. The transverse fluctuations were quantified in terms of their standard deviations $(X-X_{median})'/d_1 = 0.145$ at a given time. The characteristic transverse wave length of roller toe perimeter was approximately 1.2 times the initial flow depth d_1. Both the standard deviation of toe perimeter location and characteristic transverse wave length data were comparable to field observations in the Qiantang River bore (China).

(2) The celerity of the roller toe fluctuated rapidly with time and transverse distance, although in a quasi-two-dimensional manner on average. Instantaneous negative celerity data were recorded. The results were comparable with video frame rates between 50 fps and 480 fps, but quantitative differences were seen at a lower frame rate.

(3) The sidewalls had little effect on the upstream propagation of the breaking bore roller within the experimental flow conditions.

(4) The instantaneous longitudinal free-surface profile of the roller showed significant temporal and spatial fluctuations. The standard deviation of the free-surface elevation was maximum in the first half of the roller and the data were comparable to previous studies in breaking tidal bores and stationary hydraulic jumps for a similar Froude number.

(5) For $Fr_1 < 2$, a gradual rise in free-surface was clearly observed ahead of the turbulent roller, and both the roller toe elevation and fluctuations in vertical elevation of roller toe decreased with increasing Froude number. The dimensionless roller toe elevation Z/d_1 tended to unity and the fluctuations in roller toe elevation tended to zero for $Fr_1 > 2$, while, for $Fr_1 < 1.3$, the bore was undular and the roller disappeared.

(6) The air-water flow measurements highlighted some distinctive air bubble entrainment at the toe of the roller. Bubbles with larger chord times were detected at higher vertical elevations in a more intermittent fashion, when the sensor interacted with the upper free-surface.

Altogether the study demonstrated that the propagation of breaking bore was a very turbulent process. Although the bore may be analysed using the continuity and momentum principle in an integral form in first approximation, the rapid fluctuations in roller toe perimeter and free-surface profiles indicated a strongly three-dimensional turbulent flow motion.

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